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Ballistic Performance Testing of Aluminum Alloy 5059-H131 and 5059-H136 for Armor Applications

by Dwight D. Showalter, Brian E. Placzankis, and Matthew S. Burkins

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Weapons and Materials Research Directorate, ARL

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14. ABSTRACT

The U.S. Army Research Laboratory (ARL) was tasked to investigate the ballistic performance of aluminum alloy (AA) 5059 to determine if it was a desirable alternate alloy for use as vehicle armor. Current alloys, such as AA5083 and AA7039, have high yield and tensile strengths and provide increased ballistic protection but have significantly less corrosion resistance than AA5059. AA5059 generally provides greater ballistic protection levels than AA5083 but did not match the levels of AA7039. However, it does contain some of the desirable characteristics of the lower strength AA5083, mainly superior corrosion resistance. The combination of increased strength and corrosion resistance makes AA5059 an ideal choice for consideration as an alternate aluminum armor.

15. SUBJECT TERMS
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Table of Contents

List of Figures

List of Tables

1. Introduction

Current and future U.S. Army and U.S. Marine Corps (USMC) vehicle deployments require lightweight armor designs with improved survivability to maintain mission performance. Historically, Aluminum Alloy (AA) 5083-H131 has been used in systems such as the M1113, the M109, and the USMC Amphibious Assault Vehicle (AAV), in accordance with specification MIL-DTL-46027J (*1*). This alloy is preferable because of its lighter weight, ease of weldability for manufacturing purposes, level of performance against fragmentation based threats, and excellent corrosion resistance.

With the advent of more lethal threats, recently designed aluminum armor based systems, such as the M2 Bradley Fighting Vehicle and the USMC Expeditionary Force Vehicle (EFV), have incorporated higher strength AAs, such as AA7039 (*2*), AA2219 (*3*) and AA2519 (*4*). These alloys provide increased ballistic protection against armor piercing (AP) threats due to their higher strength. The characteristically higher yield and tensile strengths are very desirable for hull designs as they allow for reduced weight. However, these alloys have significantly less corrosion resistance than AA5083-H131. This is due to stress corrosion cracking in AA7039 and from pitting and exfoliation in AA2519 (*5*). Irrespective of cause, the lack of corrosion resistance has serious detrimental implications for maintenance requirements and the ease of coating applications. These deficiencies can also have environmental consequences due to the need for mitigating hexavalent chromium based protection schemes.

AA5083-H131 has many of the desirable traits discussed above, but the lower strength results in reduced survivability against robust AP threats. An alternate AA that delivered the positive characteristics of AA5083-H131 along with increased strength and mechanical properties for improved performance against AP threats would be an ideal future material for new vehicle production and repair of new and existing aluminum based systems.

A possible solution to fill this role is AA5059-H131. This alloy is a magnesium (Mg) based non heat treatable alloy that is strengthened by mechanical strain hardening and is produced in Koblenz, Germany, by Aleris International, Inc. (*6*). This strain hardening process results in the 5000 series alloy receiving the "H" designation rather than the "T" designation that is typical for heat treatable alloys. AA5059 contains greater amounts of Mg than AA5083 as well as some additional zinc (Zn) and zirconium (Zr) for grain refinement. Composition and mechanical properties for AA5083, AA5089, and other military specification armors are listed for comparison in tables 1 and 2, respectively.

Table 1. Chemical composition requirements for qualified military specification aluminum armor alloys (%).

Element	5083	5456	5059	7039	2219	2519
Silicon	0.40 max	0.25 max	0.50 max	0.30 max	0.20 max	0.25 max
Iron	0.40 max	0.40 max	0.50 max	0.40 max	0.30 max	0.30 max
Copper	0.10 max	0.10 max	0.40 max	0.10 max	5.8 - 6.8	5.3 - 6.4
Manganese	0.4 - 1.0	0.5 - 1.0	0.60 - 1.2	0.10 - 0.40	0.20 - 0.40	0.10 - 0.50
Magnesium	4.0 - 4.9	4.7 - 5.5	5.0 - 6.0	2.3 - 3.3	0.02 max	0.05 - 0.40
Chromium	0.05 - 0.25	0.05 - 0.20	0.30 max	0.15 - 0.25	-	-
Zinc	0.25 max	0.25 max	0.40 - 1.5	3.5 - 4.5	0.10 max	0.10 max
Titanium	0.15 max	0.20 max	0.20 max	0.10 max	0.02 - 0.10	0.02 - 0.10
Zirconium	-	-	0.05 - 0.25	-	0.10 - 0.25	0.10 - 0.25
Vanadium	-	-	-	-	0.05 - 0.15	0.05 - 0.15
Others (each)	0.05 max	0.05 max	0.05 max	0.05 max	0.05 max	0.05 max
Others (max)	0.15 max	0.15 max	0.15 max	0.15 max	0.15 max	0.15 max
Aluminum	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder

Table 2. Minimum mechanical requirements for military specification aluminum armor alloys.

Property	5083	5456	5059	7039	2219	2519
Yield Stress (ksi) (0.2% offset min.)	35.0	35.0	44.0	51.0	46	58.0
Ultimate Stress (ksi)	45.0	45.0	57.0	60.0	62.0	68.0
Percent Elongation	8	8	8	9	7	7

Marine grade tempers of 5059, such as H116 and H321, have been commercially available for quite some time on yachts, ferries, and catamarans, but little information is known on the H131 temper applicable for use in armor plate. AA5059-H136 was also investigated to a lesser degree and the results will be discussed briefly in this report. The H136 designation indicates that during the production process, the plate was only stretched and not cold rolled. This resulted in a lower cost, more ductile version that may provide some benefit as structural material supporting ceramic tiles.

In 2004, a Foreign Comparative Test (FCT) proposal was submitted to the Office of the Secretary of Defense (OSD) to investigate the possibility of using AA5059-H131 as an armor repair material for use on battle damaged or cracked armor plate sections on M2 Bradley Fighting Vehicle hulls. The project received initial approval but went unfunded for fiscal year (FY) 2005. It was eventually funded for FY 2006. Project goals included verifying ballistic performance (7), blast resistance, weldability, corrosion due to sensitization, general corrosion, and Chemical Agent Resistant Coatings (CARC) compatibility, with an ultimate goal to update or create a military specification to include this alloy if proven successful.

For the ballistic performance evaluation, V_{50} testing is currently required for all existing aluminum armor alloys. This testing produced corresponding minimum V_{50} acceptance standards for alloys AA5083 and AA7039. The results of the ballistic testing of the AA5059 alloy and its comparison to the ballistic acceptance standards of the AA5083, due to its increased corrosion resistance, will be the main focus of this report. The acceptance standards for the higher strength AA7039 will also be used for some ballistic comparison as well, but the AA5083 will remain the baseline.

2.   Experimental Procedure

The main experimental procedure required to compare the AA5059-H131 to the existing specifications was to obtain the V_{50} ballistic limit for each thickness of aluminum plate against the corresponding specified threat. For this investigation, the AA5083 specification was used for testing of AA5059-H131. The test methodology is described in detail in MIL-STD-662 (*8*) specification. The V_{50} is the velocity at which an equal number of impact complete penetration (target is defeated) and partial penetration (target is not defeated) velocities are attained using the up-and-down firing method. Fair impact is defined as occurring when a projectile or fragment simulator with an acceptable yaw strikes the target at a distance of at least two projectile diameters from a previously damaged impact area or edge of plate. A complete penetration is determined by placing a 0.020 in. 2024 T3 aluminum witness plate 6 in. behind and parallel to the target. If any penetrator or target fragment strikes this witness plate with sufficient energy to create a hole through which light passes, it is considered a complete penetration. A partial penetration is any impact that is not a complete penetration. For the AA5083 specification, it is required that four velocities, resulting in two complete penetrations (CPs) and two partial penetrations (PPs), be obtained within a velocity spread of 60 ft/s. Alternately, the specification can be met if six velocities, three CPs and three PPs, are obtained within a velocity spread of 90 ft/s. The average velocities are then computed to determine the V_{50} ballistic limit. This V_{50} ballistic limit can then be compared to the corresponding ballistic limits for other alloys to determine the relative performance.

3.   Test Projectiles

The AA5059 samples ranged in nominal thickness from 0.500 up to 3.00 in. The corresponding test projectiles and plate obliquities required for each thickness are listed in table 3.

Table 3. Projectile and obliquity requirements for ordered thicknesses.

Ordered Thickness (in.)	Projectile	Angle of Obliquity (°)
0.500–0.749	0.30 cal AP	30
0.750–1.000	0.50 cal FSP	0
1.001– 1.700[a]	20 mm FSP	0
1.001–2.000 [a]	0.30 cal AP M2	0
2.001–3.000	0.50 cal AP M2	0

Note: Cal = caliber and FSP = Fragment simulating projectile.
[a]Two types of projectiles are required for the thickness range of 1.001 to 1.700 in.

The 0.30 cal AP M2 steel core weighs 5.2 g and with the copper jacket and lead filler, the total projectile weight is 10.6 g. The total length of the projectile is 35.6 mm (1.4 in.). This projectile is shown in figure 1.
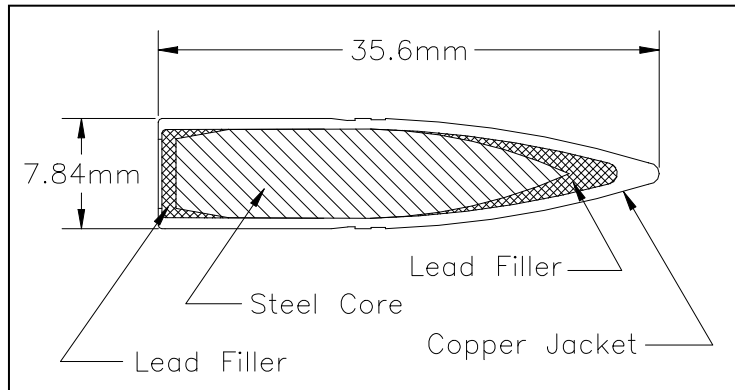

Figure 1. The 0.30 cal AP M2.

The 0.50 cal AP M2 also has a steel core along with a copper jacket and lead filler. The steel core weighs 25.4 g while the total weight is 44.9 g. The total length is 57.5 mm (2.26 in.). Figure 2 shows this projectile in detail.
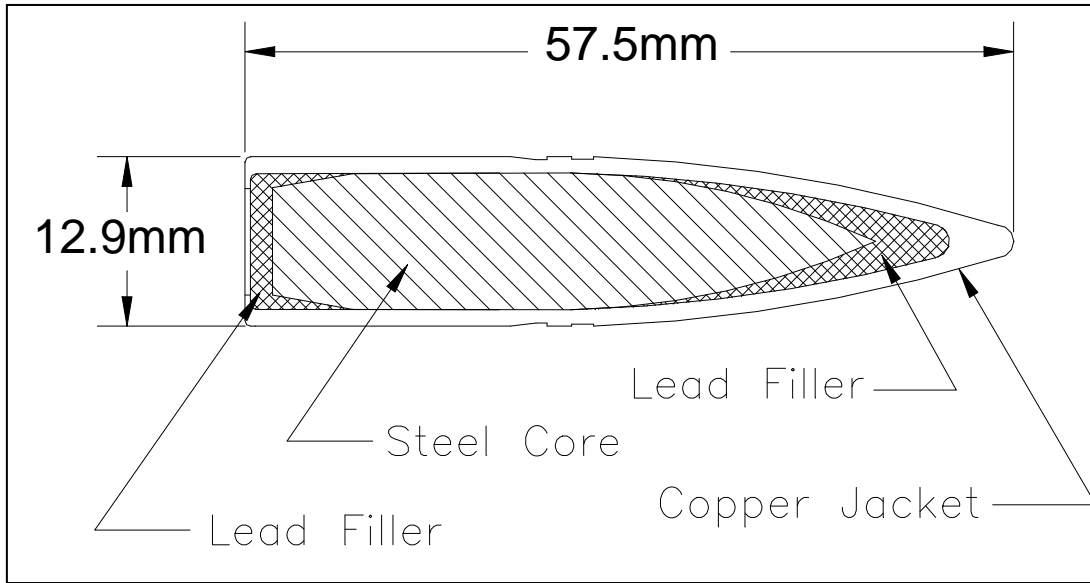
Figure 2. The 0.50 cal AP M2.

FSPs are a family of similarly shaped projectiles that are used to simulate artillery fragments. The 0.50 cal FSP, weighing 13.4 g, and the 20 mm FSP, weighing 53.8 g, are required for testing some thicknesses of aluminum according to MIL-DTL-46027. A generic sketch of the FSPs was adapted from MIL-DTL-46593B and provided as figure 3.
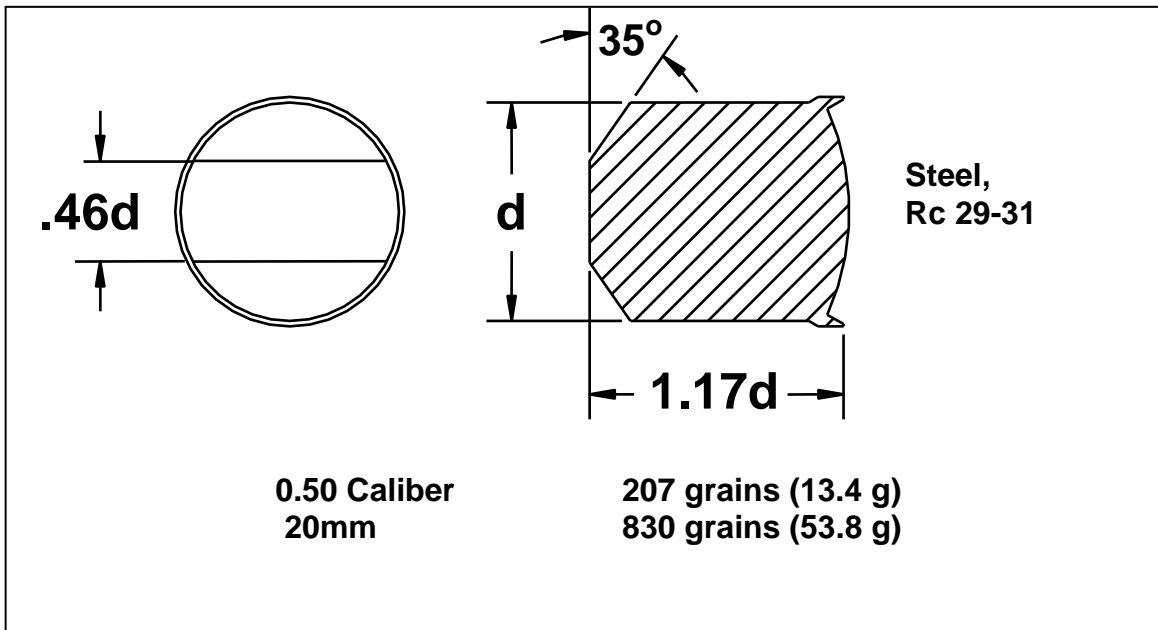

Figure 3. A generic sketch of the FSP adapted from MIL-DTL-46593B.

4.   Results and Discussion

As previously discussed, for this investigation, the AA5083 specification (MIL-DTL-46027J) was used to determine the V_{50} testing requirements for the AA5509 plates. The thinnest of these plates (approximately 0.500 to about 0.750 in.) were tested against the 0.30 cal AP M2 at a 30° obliquity. The results are shown in table 4.

Table 4. AA5059 versus 0.30 cal AP M2 at 30°.

Temper	Heat Number	Thickness (in.)	BHN	Projectile	Angle of Obliquity (°)	V_{50} (ft/s)	Standard Deviation (ft/s)
H131	211029-1A2	0.505	118	0.30 AP M2	30	1428	29
H131	162418	0.522	121	0.30 AP M2	30	1481	10
H131	966377-1-15	0.529	116	0.30 AP M2	30	1475	21
H131	975418	0.588	121	0.30 AP M2	30	1606	18
H131	966378-1-5	0.742	121	0.30 AP M2	30	1834	22
H131	211030-2A1	0.779	118	0.30 AP M2	30	1922	21
H131	157241	0.782	124	0.30 AP M2	30	1915	22
H136	186064-1A2	0.488	107	0.30 AP M2	30	1380	22
H136	186063	0.751	112	0.30 AP M2	30	1822	11

Note: BHN = Brinell Hardness Number

The temper number for this table and all subsequent ones indicates how the material was produced. H131 indicates that during the production process, the material was strengthened by mechanical strain hardening. Temper number H136 indicates that the material was only stretched, and not cold rolled. These data are plotted in figure 4.
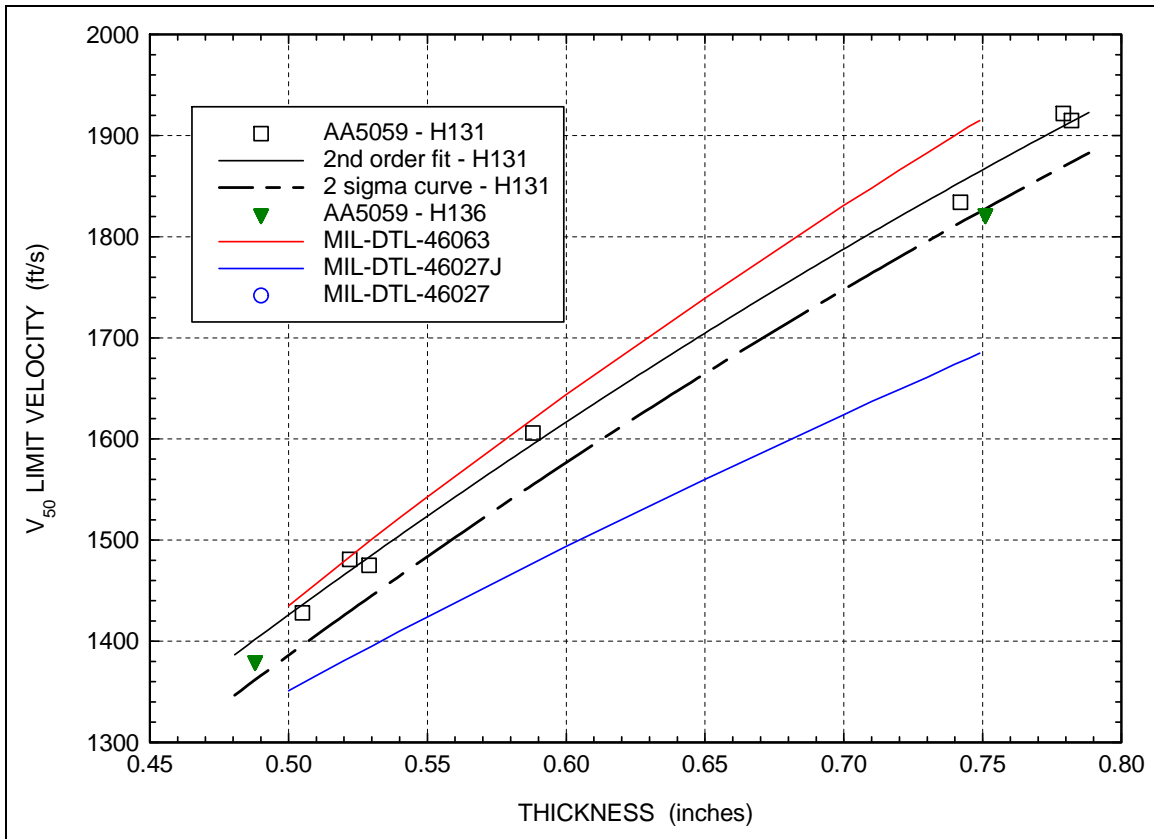
Figure 4. The 0.30 cal AP M2 versus AA5059 at a 30° obliquity.

Figure 4 plots the V_{50} versus the plate thickness for each plate and temper tested, as well as the military specification requirements for AA5083 (MIL-DTL-46027J) and AA7039 (MIL-DTL-46063). The 2 sigma curve (V_{50} – 2 standard deviations) is also plotted for AA5059-H131. This 2 sigma curve is required to account for the fact that the V_{50} only provides the velocity at which the armor defeats the penetrator 50% of the time. Subtracting the 2 standard deviations from the V_{50} velocity provides a velocity at which, statistically, the armor will defeat the penetrator about 98% of the time. Therefore, the actual curve that is used to compare to the specification requirements is the 2 sigma curve.

Using the 2 sigma curve that is depicted by the black dashed line, it can be determined that the V_{50} ballistic limit velocities for this range of thicknesses (0.488 to 0.782 in.) against the 0.30 cal AP M2 at 30° seem to lie almost exactly at the midpoint between the V_{50} limit velocities for the AA7039 and AA5083 minimum requirement. This indicates the material provides increased ballistic performance over the AA5083, but lower performance as compared to AA7039. However, the AA5083 (due to its increased corrosion resistance) is the baseline for comparison. For all thicknesses tested, the AA5059 provided increased ballistic performance over the AA5083 minimum requirement.

The MIL-DTL-46027J specification required plates with nominal gauge thicknesses from about 0.750 to approximately 1.000 in. to be tested against the 0.50 cal FSP at a 0° obliquity. Table 5 lists these results and the data from table 5 are depicted graphically in figure 5

Table 5. AA5059 versus 0.50 cal FSP at 0°.

| Temper	Heat Number	Thickness (in.)	BHN	Projectile	Angle of Obliquity (°)	V_{50} (ft/s)	Standard Deviation (ft/s)
H131	966378-1-5	0.742	121	0.50 cal FSP	0	1830	33
H131	211030-2A1	0.780	118	0.50 cal FSP	0	2070	32
H131	157241	0.782	124	0.50 cal FSP	0	1991	8
H131	966379-1-24	0.793	121	0.50 cal FSP	0	1990	16
H131	799479-9	0.804	126	0.50 cal FSP	0	2126	24
H131	966381-1-22	0.847	121	0.50 cal FSP	0	2267	16
H131	966381-1-8	0.928	121	0.50 cal FSP	0	2534	31
H131	966384-1-5	0.990	121	0.50 cal FSP	0	2810	16
H131	211058	1.001	126	0.50 cal FSP	0	2978	22
H131	162331	1.035	126	0.50 cal FSP	0	3202	31
H136	186063	0.751	112	0.50 cal FSP	0	1834	24
H136	185919-1B1	1.006	109	0.50 cal FSP	0	2848	31
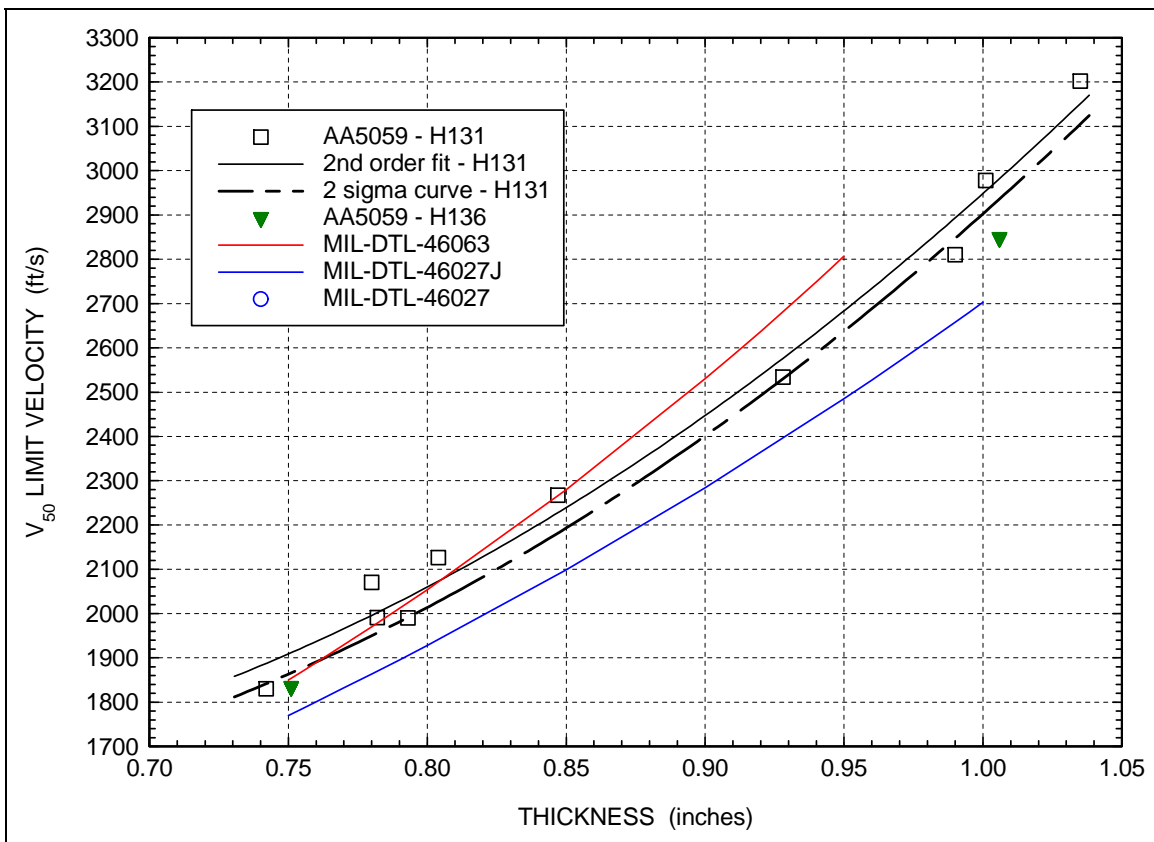
Figure 5. The 0.50 cal FSP versus 5059AA at a 0° obliquity.

From this data, it can be seen that for each thickness plate tested, the AAA5059-H131 (black dashed line) provided increased ballistic protection in comparison to the AA5083 requirement and actually, at a thickness of 0.742 in., provided slightly increased protection as compared to the AA7039 requirement. Additionally, the H136 temper provided greater ballistic protection than the AA5083 at all thicknesses, though it did not outperform the AA5083-H131.

Plates with thicknesses of approximately 1.0 up to about 1.8 in. were tested against both the 20 mm FSP at 0° and the 0.30 cal AP M2 at 0°. Table 6 lists the results against the 20 mm FSP. These data are plotted versus the AA5083 and AA7039 specifications in figure 6.

Table 6. AA5059 versus 20 mm FSP at 0°.

| Temper	Heat Number	Thickness (in.)	BHN	Projectile	Angle of Obliquity (°)	V_{50} (ft/s)	Standard Deviation (ft/s)
H131	966384-1-15	0.990	118	20 mm FSP	0	1375	20
H131	966384-1-5	0.990[a]	121	20 mm FSP	0	1396	28
H131	7994890	1.003 [a]	116	20 mm FSP	0	1496	29
H131	211058	1.001	126	20 mm FSP	0	1469	31
H131	162331	1.035	126	20 mm FSP	0	1544	22
H131	799480	1.197	116	20 mm FSP	0	1900	23
H131	966383-1-10	1.364	114	20 mm FSP	0	2231	20
H131	975421-1D3	1.491	116	20 mm FSP	0	2628	26
H131	162335	1.531	121	20 mm FSP	0	2784	21
H131	966388	1.881	107	20 mm FSP	0	3976	13
H136	185919	1.006	109	20 mm FSP	0	1420	17
H136	186092	1.522	107	20 mm FSP	0	2555	29
H136	185932-1-2	2.005	105	20 mm FSP	0	4076	23

[a]Repeat shots

9
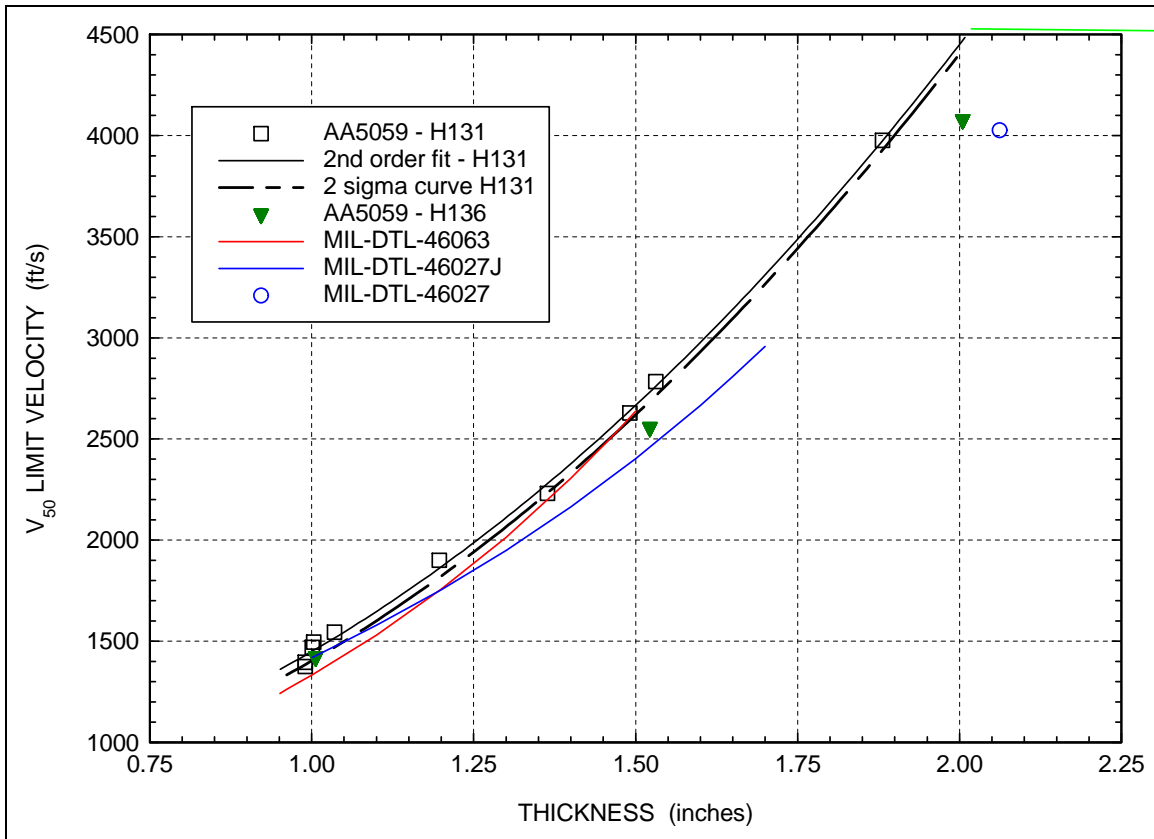
Figure 6. The 20 mm FSP versus AA5059 at a 0° obliquity.

The H131 temper, depicted by the black dashed line, provided increased ballistic protection compared to the AA5083 at all thickness above 1.00 in. However, at thickness of approximately 1.00 in. (0.990–1.035 in.), the data shows some points where the ballistic protection, determined experimentally for AA5059-H131, falls below the performance provided by the AA5083. Because of this, some repeat tests were conducted at thickness around 1.00 in., which showed a slightly better performance that exceeded the AA5083 levels. At thickness ranging from 1.00 up to about 1.25 in., the H131 temper actually outperformed the AA7039 specification as well. The H136 temper provides a slight increase ballistic performance over the AA5083 specification at thicknesses greater than 1.25 in., but not at thicknesses less than 1.25 in. The AA7039 actually provides slightly less ballistic protection than the AA5083 at thickness below about 1.20 in., which is depicted graphically in figure 6. For the range of thicknesses from about 1.00 to 1.2 in., the H136 temper actually performed better ballistically that the AA7039 specification.

The specification also called for these plate thicknesses to be tested against the 0.30 cal AP M2 at 0°. The results for this threat are shown in table 7 and are shown graphically in figure 7.

10

Table 7. AA5059 versus 0.30 cal AP M2 at 0°.

| Temper	Heat Number	Thickness (in.)	BHN	Projectile	Angle of Obliquity (°)	V_{50} (ft/s)	Standard Deviation (ft/s)
H131	966384-1-15	0.990	118	0.30 AP M2	0	1928	21
H131	211058	1.001	126	0.30 AP M2	0	1935	34
H131	162331	1.035	126	0.30 AP M2	0	2000	14
H131	799480	1.197	116	0.30 AP M2	0	2168	26
H131	966386-1-10	1.364	114	0.30 AP M2	0	2310	27
H131	975421-1D3	1.492	116	0.30 AP M2	0	2502	28
H131	162335	1.531	121	0.30 AP M2	0	2536	16
H131	966388	1.881	107	0.30 AP M2	0	2818	20
H131	211054	2.016	126	0.30 AP M2	0	2974	31
H131	186497	2.022	121	0.30 AP M2	0	2992	21
H136	185919-1B1	1.006	109	0.30 AP M2	0	1914	21
H136	186092	1.522	107	0.30 AP M2	0	2422	26
H136	185932	2.009	105	0.30 AP M2	0	2865	25
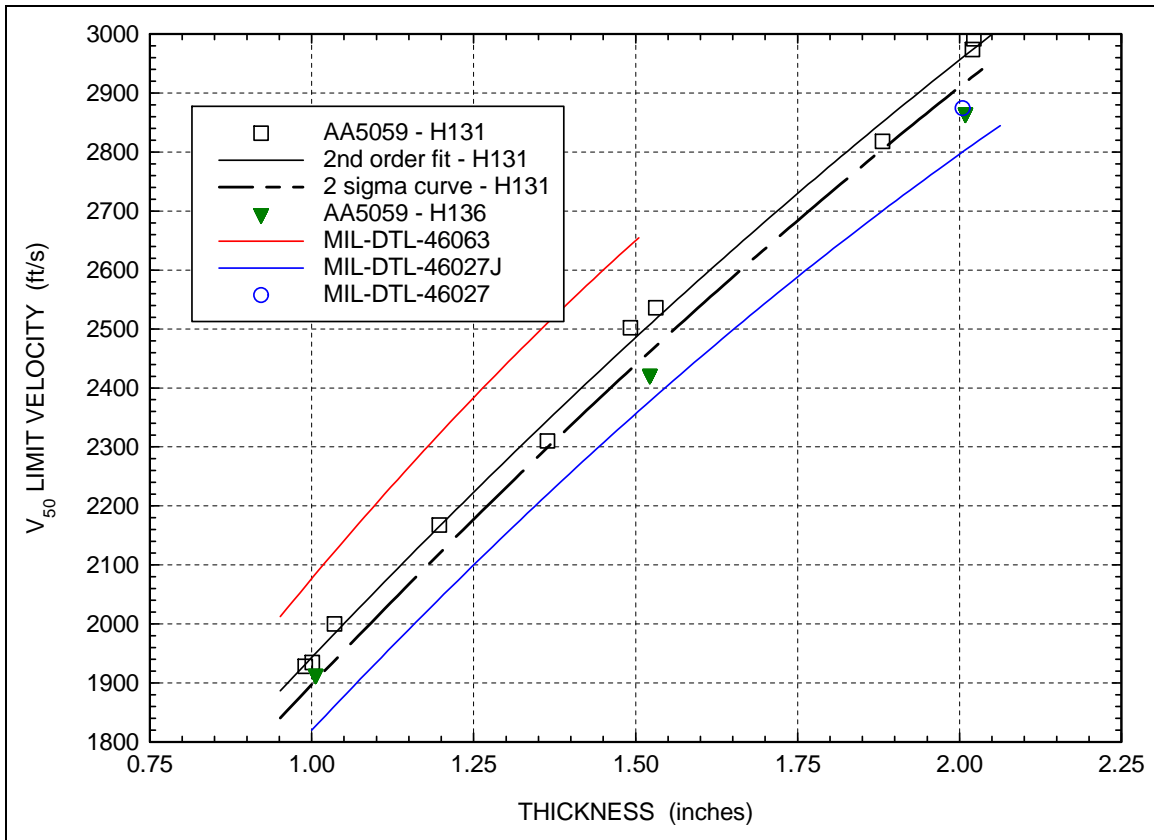
Figure 7. The 0.30 cal AP versus AA5059 at a 0° obliquity

For the .30 cal AP at 0°, the AA5059 alloy provided greater ballistic protection than the AA5083 specification for all nominal thicknesses from 1.00 to 2.00 in., while falling short of the protection levels for AA7039. The H136 slightly exceeded the performance of the AA5083 specification for thickness up to around 1.35 in., while providing essentially equal performance for thicker gauges.

The thickest gauge plates (about 1.8 to 3.0 in.) were required by the specification to be tested against the 0.50 cal AP M2 round. The results for these tests are shown in table 8. This data is graphically represented against the other alloys in figure 8.

Table 8. AA5059 versus 0.50 cal AP M2 at 0°.

| Temper	Heat Number	Thickness (in.)	BHN	Projectile	Angle of Obliquity (°)	V_{50} (ft/s)	Standard Deviation (ft/s)
H131	966388	1.881	107	0.50 AP M2	0	2167	36
H131	211054	2.016	126	0.50 AP M2	0	2230	15
H131	186497	2.022	121	0.50 AP M2	0	2199	21
H131	975423	2.427	121	0.50 AP M2	0	2481	25
H131	186116	2.527	114	0.50 AP M2	0	2472	37
H131	245382-1B1	2.539	114	0.50 AP M2	0	2522	19
H131	966390-9	3.006	99	0.50 AP M2	0	2736	23
H131	170077	3.014	105	0.50 AP M2	0	2689	31
H136	185932	2.009	105	0.50 AP M2	0	2123	11
H136	185996-1A2	2.530	103	0.50 AP M2	0	2436	24
H136	185980-1H1	3.036	109	0.50 AP M2	0	2724	10
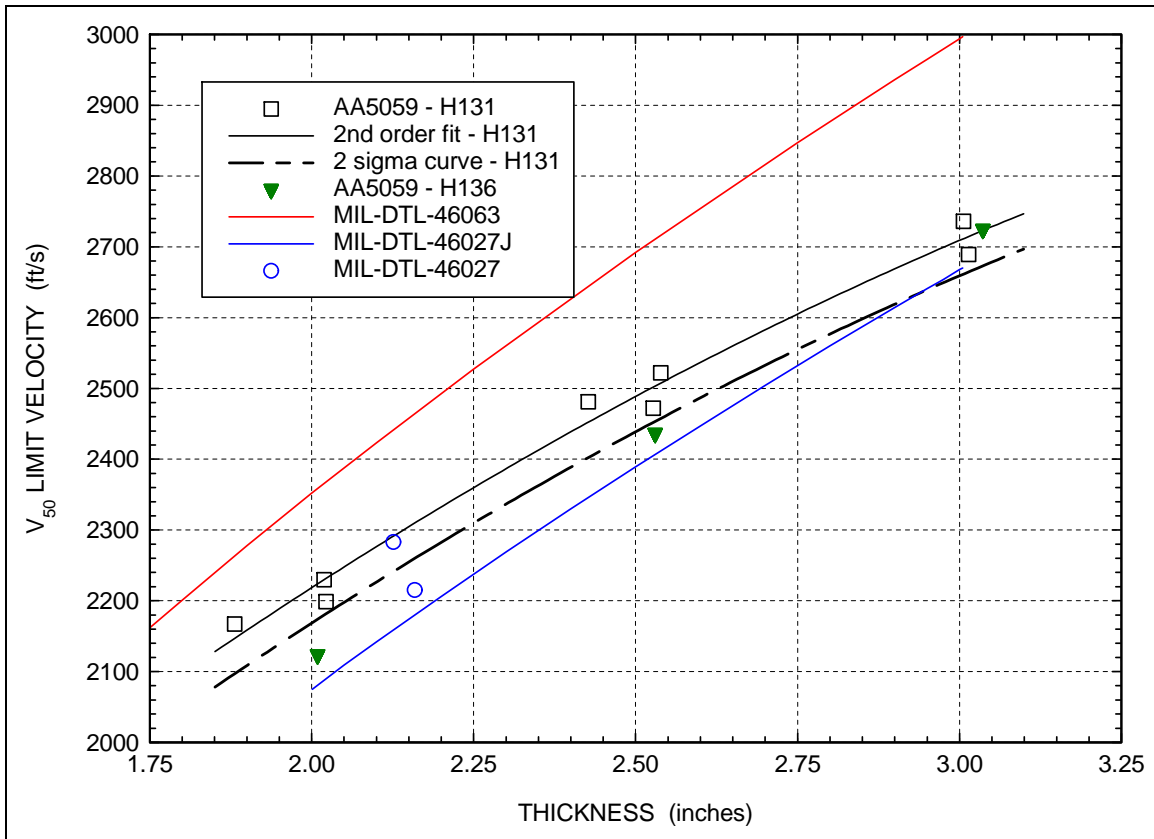
Figure 8. The 0.50 cal AP versus AA5059 at a 0° obliquity.

For the 0.50 cal AP at 0°, it can be seen that the AA5059-H131 provided increased ballistic protection relative to AA5083 for thickness from about 1.8 up through 2.5 in. However, at thicknesses of approximately 3.00 in., the protection levels were about equal or slightly less than AA5083. The protection was significantly less than the levels provided by AA7039 for all thicknesses. As for the H136 temper, the protection provided was approximately equal to AA5083 for all thickness while substantially less than AA7039.

It is necessary to say a few words about the failure modes of the various alloys with respect to FSPs. Figure 9 shows some interesting comparisons of the response of the three alloys investigated in this study. Figure 9a shows the response of AA7039 to a 20 mm FSP while figures 9b and 9c show the response of AA5083 and AA5089, respectively, to the same threat for equal thickness plates at approximately the same velocity.

13

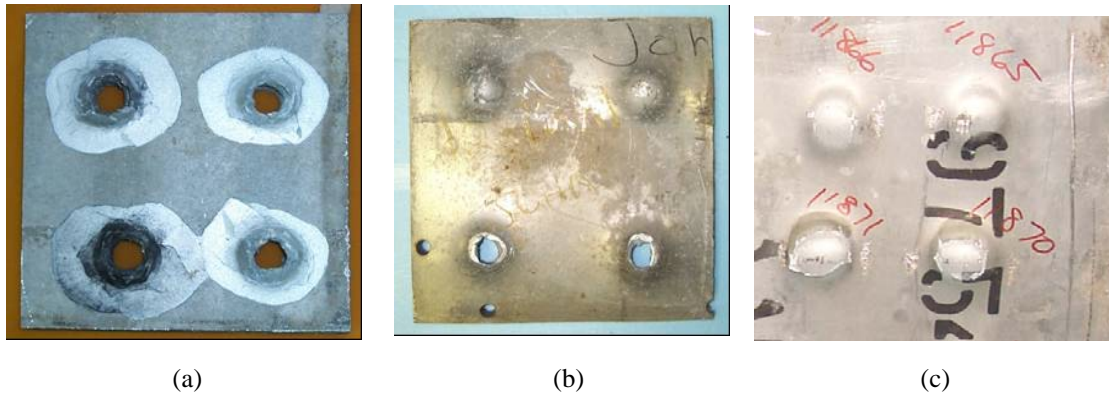<div align="center">(a)   (b)   (c)</div>

Figure 9. Comparison of (a) AA7039, (b) AA5083, and (c) AA5059.

The AA7039 (figure 9a) exhibits severe spalling, where large portions of the material have torn away from the exit hole and present a serious problem with respect to behind armor debris damage. The AA5083 in figure 9b shows the more ductile plugging effect where the material bulges with the FSP and there are no large chucks of metal breaking off to cause more damage behind the armor. Figure 9c shows the ductile behavior and plugging effects of the AA5059, which is very similar to the AA5083. This ductile behavior is an extremely desirable characteristic for armor materials to be incorporated in vehicle design, especially as a base armor to absorb shock and to support other armor materials.

5. Summary

AA5059 generally provides greater ballistic protection levels, based on the V_{50} limit velocity and 2 sigma curve criteria, than the AA5083 specification. This holds true for almost every thickness against FSPs and AP rounds. In most cases, the ballistic protection levels do not match that of the higher strength AA7039 specification; however, AA5059, while providing an increased level of ballistic protection due to its higher strength, also has some of the very desirable characteristics of the lower strength AA5083 that are not present in AA7039. The main such trait is the vastly superior corrosion resistance of AA5059 as compared to AA7039, which is an invaluable quality in terms of maintenance and repair of existing systems. AA5059-H131 also exhibits the increased ductility in failure mode against FSP threats that is not present in the AA7039, which is also extremely beneficial in terms of overall performance.

6. Conclusions

AA5083-H131 has many desirable traits, but is deficient against AP threats compared to AA7039 alloys due to its lower strength. AA5059 provides increased mechanical properties, most notably higher strength and thus increased ballistic performance against AP threats, while also having the positive corrosion resistance characteristics not present in AA7039. This combination of increased ballistic protection along with superior corrosion resistance makes AA5059 an ideal choice for consideration as an alternate aluminum armor for production and repair of existing systems.

The performance of AA5059 in this study resulted in the preparation of a new military specification to include this alloy, MIL-DTL-46027K (*9*). It was rewritten from the 5083/5456 MIL-DTL-46027J specification to cover three classes of 5000 series alloys: Class 1 (5083), Class 2 (5456), and Class 3 (5059). Under this revised format, additional 5000 series alloys can be added in the future.

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Acronyms

AA	Aluminum Alloy
AAV	Amphibious Assault Vehicle
AP	armor piercing
BHN	Brinell Hardness Number
CARC	Chemical Agent Resistant Coatings
CPs	complete penetrations
EFV	Expeditionary Force Vehicle
FCT	Foreign Comparative Test
FSPs	Fragment simulating projectiles
FY	fiscal year
OSD	Office of the Secretary of Defense
PPs	partial penetrations
USMC	U.S. Marine Corps
Zn	zinc
Zr	zirconium

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